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I, JANENE PEISKER, TEAM LEADER EXAMINATION SUPPORT AND SALES hereby certify that annexed is a true copy of the Provisional specification in connection with Application No. 2004900213 for a patent by COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION as filed on 16 January 2004.

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WITNESS my hand this
Twenty-seventh day of January 2005

J. K. H.

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AUSTRALIA

Patents Act 1990

PROVISIONAL SPECIFICATION

Applicant:

COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION

Invention Title:

SULPHUR DIOXIDE DETECTION METHOD

The invention is described in the following statement:

SULPHUR DIOXIDE DETECTION METHOD

Field of the Invention

The invention relates to a sulphur dioxide detection method and apparatus.

Background to the Invention

Volcanic ash and sulphur dioxide clouds constitute a serious hazard to aircraft even after the clouds have moved from the site of a volcanic eruption. Apart from containing ash particles, the clouds include gases such as SO_2 which after a few days oxidises and hydrolises to form sulphuric acid droplets, either as an ash-acid mixture or as a coating over ash particles. Both the ash particles and the sulphuric acid droplets of volcanic ash clouds are capable of causing significant damage to and possible loss of an aircraft which encounters an ash cloud.

A number of aircraft encounters with volcanic ash clouds or sulphur dioxide clouds have been recorded in the past where significant damage has occurred. It will be appreciated that the sulphur dioxide may be found in areas separate from the volcanic ash. In the year 2000, a National Aeronautics and Space Administration (NASA) DC-8 Airborne Sciences research airplane flew through what was described as a diffuse volcanic ash cloud from the mount HEKLA Volcano when flying from Edwards, California to Kiruna, Sweden. The ash cloud was not visible to flight crew, however, the science research airplane carried sensitive research equipment which was capable of detecting the sulphur dioxide. In-flight checks and post-flight visual inspections revealed no damage to the airplane. However, detailed examination of the engines revealed damage to some of the turbine cooling passages.

Furthermore, high levels of sulphur were found in the oil.

It seems likely that this ash cloud actually was predominantly a sulphur dioxide cloud. Even if it was not, it raises the possibility that an aircraft can fly through sulphur dioxide without passing through ash. The post encounter treatment of the engine in the case of sulphur dioxide encounter would be different to and considerably cheaper than the equivalent treatment required of an engine during an ash encounter.

Accordingly, it would be desirable to provide a sulphur dioxide detection technique.

Summary of the Invention

The present invention relates to a method of detecting sulphur dioxide clouds comprising:

measuring infrared radiation at a viewing elevation at or above the horizon and at a key wavelength at which there is an SO_2 feature and in the vicinity of which there is a region where the amount of infrared radiation from water vapour in the atmosphere varies in accordance with a predetermined relationship;

measuring radiation at two or more subsidiary wavelengths in said region;

determining the amount of radiation from water vapour at the key wavelength from the measured radiation at the subsidiary wavelengths using the predetermined relationship;

determining whether a sulphur dioxide cloud is present from the measured infrared radiation at the key wavelength and the determined amount of radiation from water vapour.

Preferably, said subsidiary wavelengths are located either side of said key wavelength.

The inventor has determined that the key wavelength should be selected from the group of 4μm, 7.3μm, and 8.6μmand that 7.3μm is the preferred key wavelength.

Where the key wavelength is 7.3μm, it is preferred that subsidiary wavelengths at ±0.5μm are used. The inventor has established that for the region of these wavelengths the predetermined relationship is that radiation from water vapour varies in a substantially linear manner. Accordingly, the radiation from water vapour at the key wavelength can be interpolated from the radiation at the subsidiary wavelengths on the basis of this predetermined relationship. The inventor has also established that there is substantially less SO_2 absorption at this wavelength.

The method may also involve compensating for background SO_2 in the atmosphere.

The invention also provides a detection apparatus for detecting a sulphur dioxide cloud comprising:

measurement means for measuring infrared radiation at a viewing elevation at just below, or above the horizon a key wavelength at which there is an SO_2 feature and in the vicinity of which there is a region where the amount of infrared radiation from water vapour in the atmosphere varies in accordance with a predetermined relationship and for measuring infrared radiation at two or more subsidiary wavelengths in the region; and

processing means for determining the amount of radiation from water vapour at the key wavelength from the measured radiation at the subsidiary wavelengths using the predetermined relationship and determining whether a sulphur dioxide cloud is present from the measured

infrared radiation at the key wavelength and the determined amount of radiation from water vapour; and

output means for generating an output signal indicative of the presence of a sulphur dioxide cloud when a sulphur dioxide cloud is present.

The inventor has also determined that the method and apparatus of the present invention can be used to detect sulphur dioxide clouds from the ground or from an aircraft.

Brief Description of the Drawings

Figure 1 illustrates the SO_2 absorption feature in the region 1200cm^{-1} to 1500cm^{-1} and the preferred measurement wavelengths of the invention;

Figure 2 is a schematic diagram of a SO_2 detection apparatus of the preferred embodiment;

Figure 3 illustrates two modes of operation of the apparatus;

Figure 4 is a schematic diagram of apparatus to be used from an aircraft;

Figures 5a - 5c represent normal climatic conditions;

Figures 6a and 6b represent variations on normal conditions to allow testing of the invention;

Figure 7 represents variations in SO_2 for testing;

Figure 8 shows variation in temperature with SO_2 concentration; and

Figure 9 shows temperature plotted as a function of absorber amount.

Description of the Preferred Embodiment

Herein, the term "key wavelength" is used to refer to a wavelength at which there is an appropriate SO_2

feature.

Persons skilled in the art will appreciate that a "wavelength" in the context of this specification does not imply a single wavelength but rather encompasses a band of radiation. Typically the width of the band will depend on the filter used to observe/measure light at the wavelength of interest.

The term "subsidiary wavelength" is used to refer to a wavelength in a region in the vicinity of the key wavelength where a relationship can be established between radiation from water vapour at two or more subsidiary wavelengths and radiation from water vapour at the key wavelength.

The preferred embodiment provides a method and apparatus that allows identification of sulphur dioxide clouds in the free atmosphere. The apparatus of the preferred embodiment uses an infrared detector, interference filters and focussing optics. The filters divide radiation within the band between 6.8 and 8.1 µm into three narrow bands. The central bands corresponds to a strong SO_2 absorption feature caused by the anti-symmetric stretch of the SO_2 molecule. The other bands are above and below this feature. The central band B_c, is sensitive to SO_2 concentrations. The lower band, B_l and higher band B_h, are used to account for the effects of water vapour on the absorption in band B_c.

Accordingly, B_c is the key wavelength and B_l and B_h are the subsidiary wavelengths in the preferred embodiment.

Figure 1 illustrates the absorption feature due to SO_2 for the infrared region extending from 1200 cm^{-1} (8.33 µm) to 1500 cm^{-1} (6.67 µm). The ordinate in this

plot is line strength and the abscissa is wavenumber (cm^{-1}; wavelength in μm = 10,000/wavenumber in cm^{-1}). Also, shown are three idealised filter response functions which isolate radiation within the three narrow regions corresponding to: B_h (7.633-8.065 μm) B_c (7.143-7.57 μm) and B_l (6.897-7.042 μm).

The response functions are normalised to unity and scaled appropriately for plotting. The central wavenumber for the SO_2 absorption is 1363 cm^{-1} and the band extends from about 1320 cm^{-1} to about 1390 cm^{-1}. A filter covering this region responds to all the radiation from this band; whether the SO_2 feature be due to absorption or emission. In the case of a detection apparatus viewing a cold background, i.e. viewing from the ground to space or from an aircraft towards the horizon, there would be more radiation in this band in the presence of the SO_2 cloud than if it were absent.

In practice, water vapour and clouds also absorb and emit radiation in the region 7-8 μm. The inventor has realised that the two bands positioned either side of the central band are used to eliminate the effects of water vapour.

Water vapour absorbs and emits radiation throughout the region 7-8 μm. The amount of radiation absorbed or emitted depends on the amount of water vapour and on its location in the atmospheric column. Water vapour near the boundary of the earth's surface is generally warm and abundant. Water vapour near the tropopause (i.e. at jet aircraft cruising altitudes) is cold and sparse. The central band of the SO_2 detector responds to radiation due to both SO_2 and water vapour. The lower and higher bands of the detector however, are only sensitive to water vapour. The inventor has determined that the radiation from water vapour in the

region surrounding B_c behaves in a sufficiently linear manner to enable it to eliminate the effects of water vapour on the central band. The Planck blackbody radiation from B_l and B_h are linearly interpolated to estimate the radiation detected in B_c due to water vapour only. This radiation amount is subtracted from the radiation actually measured by B_c. The residual amount is due to SO_2.

A schematic of the detection apparatus is shown for illustrative purposes in Figure 2. The detection apparatus 6 consists of four major components:

- Fore-optics 1 that focus a beam of incoming infrared radiation onto a detector.
- A filter wheel 2 consisting of at least three narrow band interference filters that isolate radiation into the bands: B_l, B_c and B_h.
- An infrared detector array 3 sensitive to radiation in the 7-8 μm region.
- Processing means 4 for processing the detector signal to determine whether SO_2 and hence a sulphur dioxide cloud is present.

Figure 3 is a schematic illustrating two modes of operation of a detection apparatus 6 that senses infrared radiation in order to detect SO_2 clouds. One mode assumes that the detection apparatus 6 is on board an aircraft 7 and views the SO_2 cloud ahead at a small angle to the horizontal. The second mode assumes that the detection apparatus 6 is based on the ground and views the cloud at a large angle to the horizontal (e.g. zenith viewing).

The detection apparatus of the preferred embodiment may be operated from the ground viewing the sky above or from an aircraft viewing forwards. The principal mode of operation is anticipated to be from an aircraft with the instrument having an unobstructed view of the

atmosphere ahead of the aircraft as the method works best when water vapour concentration is less than 1g cm^{-2}. Ideally the view should be horizontal or a few degrees (3-5°) above the horizon, so that the background radiation is cold. Typically, aircraft fly with their nose at an angle of about 3 degrees to horizontal. However, the processor 4 can be configured to account for changes in viewing zenith angle, making the technique insensitive to the viewing direction. For the case of a detection apparatus 6 viewing ahead of an aircraft at a zenith angle of Z degrees, the detection apparatus 6 provides three signals to the processor 4. A synthetic signal corresponding to the amount of radiation from water vapour is determined through linear interpolation of the signals from B_l and B_h. This signal labeled $\hat{B}_c$ is compared to the signal from B_c.

The processor 4 then computes the SO_2 amount at the key wavelength B_c using $\hat{B}_c$ and the original signal B_c. The processor 4 uses pre-defined look-up tables that account for standard atmospheric conditions (tropical, mid-latitude, and polar) and the viewing geometry. The detector array 3 provides an image of the SO_2 amount with a spatial resolution that depends on the exact number of detector elements in the array (320x240 is recommended) and the distance to the SO_2 cloud. Distance information cannot be supplied by the detection apparatus 6, however, the SO_2 anomaly will be detected at distances of up to several 100 kms depending on the cruising altitude and clarity of the atmosphere ahead. The detection apparatus 6 produces an output 6 either in the form of an amount of SO_2 or an alarm signal indicating the presence of SO_2. The alarm signal may cause an audible or visual alarm in an aircraft.

Figure 4 illustrates how the apparatus works in the case of being mounted in an aircraft.

In addition to signals from the detector 3 the processor 4 also receives aircraft altitude information 8 from the aircraft and standard atmosphere information 9 from a memory associated with the processor.

Examples

A sophisticated radiative transfer model-MODTRAN (Berk, *et al.*, 1989) is used to model the response expected from a single-element detector viewing arealistic atmosphere. The viewing geometry is varied in the simulations to account for viewing from below the SO_2 cloud, viewing from above, and viewing at a small angle along a nearly horizontal path. The amount of SO_2 is varied, as is the main other gaseous absorber in the region-water vapour. We refer to the amount of SO_2 as the cloud thickness.

1. Model Atmosphere

Vertical profiles of the model atmosphere used in the simulations are shown in Figure 5 and variations used to test the present invention are shown in Figure 6 and Figure 7.

(a) *Temperature*

The temperature profile is shown in Figure 6a. Varying the profile has little effect on the retrieval and detection algorithm because the algorithm uses differences in temperatures. No further simulations were performed on this parameter because of its insensitivity.

(b) *Water vapour*

Water vapour was varied by increasing the amounts in the lowest layers from less than 0.1 cm of precipitable

water to more than 3 cm. No effect was found on the detection or retrieval because the water vapour lies below the SO_2 cloud. Water vapour was also increased in the layer that contained the SO_2 and this has a major effect. The perturbed water vapour profile is shown in Figure 6b.

(c) Sulphur dioxide

The vertical profile of the background SO_2 is taken from the US standard atmosphere. The profile corresponds to a well-mixed gas with a constant vertical concentration of 10^{-5} ppmV (parts per million by volume). Perturbed profiles, with increasing SO_2 concentration, are shown in Figure 7. Eight profiles are shown. The integrated amount of SO_2 in a vertical column for the profiles varies from 10 milli atm-cm to 100 milli atm-cm. Depending on the pathlength travelled the total absorber amount can be much larger. Results for SO_2 absorber amounts of more than 1000 milli atm-cm.

2. Viewing the SO_2 cloud along horizontal paths

For the purpose of example, model simulations have been performed for the case of horizontal viewing from a platform (e.g. an aircraft) directly ahead and towards an SO_2 cloud. The viewing direction is assumed to be horizontal at the altitude of the platform (8 km, or ≈26,000 feet is assumed). The cloud thickness (as measured in the viewing direction) is varied from 10 km to 500 km and the concentration within the cloud is varied from background levels to ≈0.1 ppmV. This range of concentration covers the smallest eruptions (that are likely to reach these heights, e.g. Hekla-style eruptions) to the largest observed this century (e.g. Pinatubo-style eruptions). The results of these model simulations are summarised in two figures. Figure 8 shows the variation of the temperature anomaly (the temperature difference

between the synthetic signal and the measured signal as a function of cloud thickness).

The family of curves 20-27 generated from the modelling are lines of constant concentration for SO_2 concentration varying from 0.0136 ppmV 20 to 0.1083 ppmV 27. The points that lie on vertical lines correspond to lines of constant cloud thickness. As the cloud thickens the curves follow the same trend with increasing anomalous signal until the cloud starts to become opaque. At this point, which varies with SO_2 concentration, the temperature anomaly increases towards a limiting value ($\Delta T \approx -2$ K). Note that the opaque limit is reached either by increasing concentration or increasing cloud thickness, since both quantities increase optical depth and hence absorption. Beyond a thickness of 500 km, the cloud is essentially opaque and the radiative process changes from absorption to emission.

Figure 9 provides an alternate way of understanding the physical processes involved in SO_2 detection. Here the temperature anomaly is plotted as a function of absorber amount. The plot tells us that for a given anomaly, several values of absorber amount are possible, depending on the cloud thickness and concentration. Thus, it is not possible to uniquely quantify the absorber amount from the temperature anomaly without knowing either the concentration or the cloud thickness. In practice it is not necessary to know these quantities, as the purpose of the invention is to detect the presence of SO_2 gas in the free atmosphere, rather than quantify the amount. The modelling does give an indication of the limits within which detection of SO_2 is possible. At the lower end, for cloud thicknesses of 10 km or less, the SO_2 concentration must be larger than $\approx$0.06 ppmV. This corresponds to an absorber amount of $\approx$25 milli atm-cm. SO_2 clouds that intercept air-routes (i.e. heights

>20,000 feet) will have horizontal dimensions of 10's of kilometres and absorber amounts well in excess of 25 milli atm-cm would be expected.

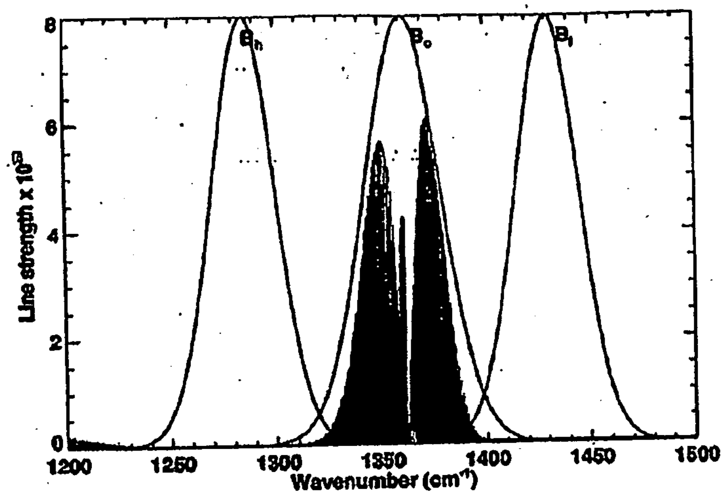

Figure 1

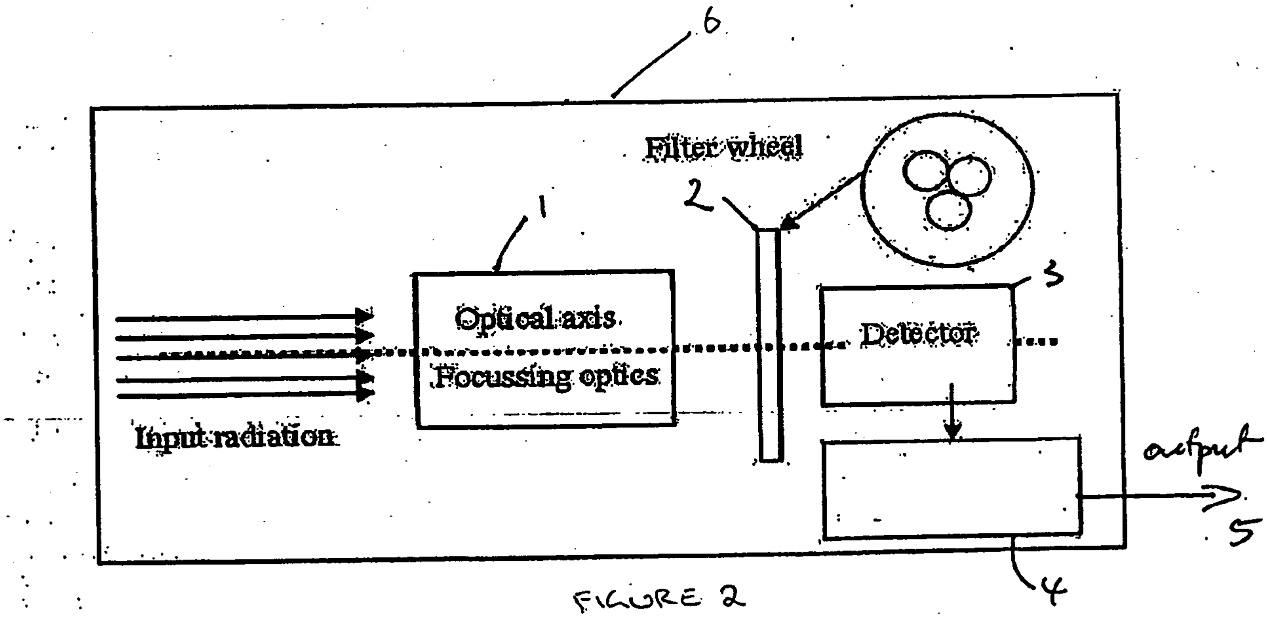

FIGURE 2

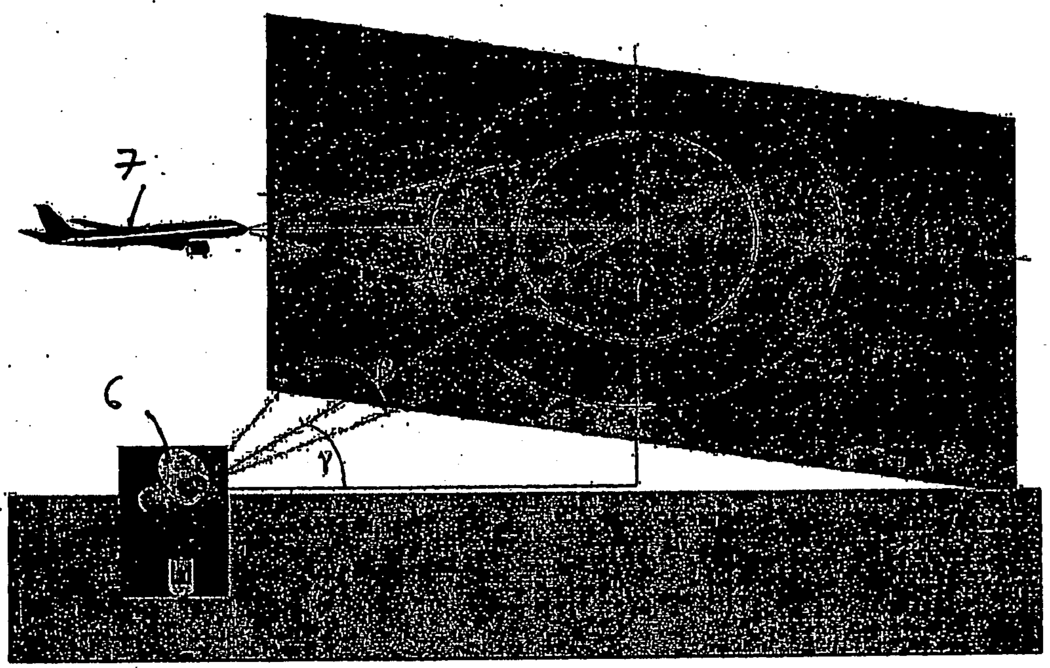

Figure 3

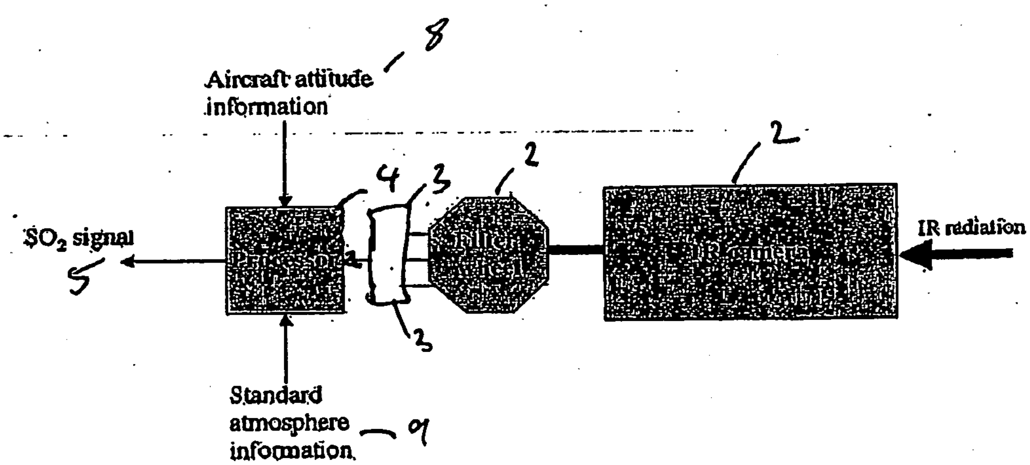

FIGURE 4

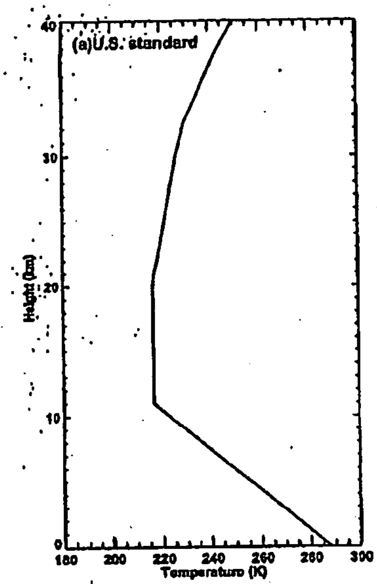

Fig 5a

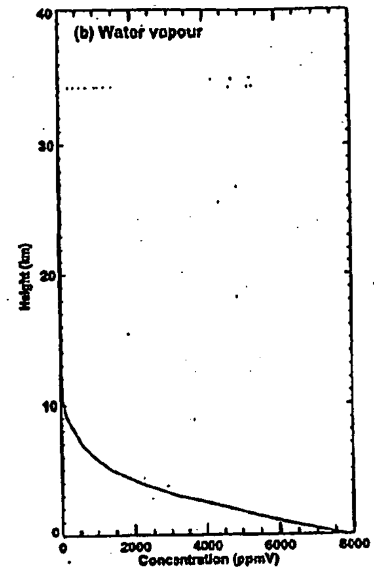

Fig 5b

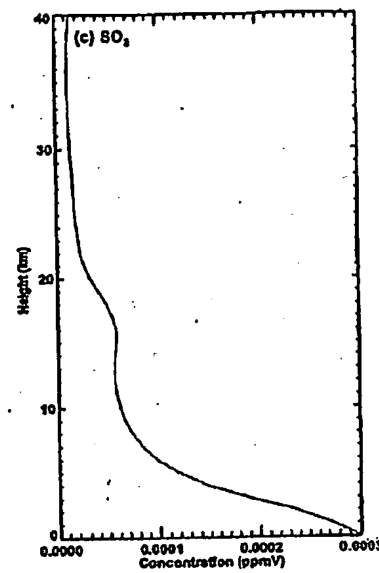

Figure 5c

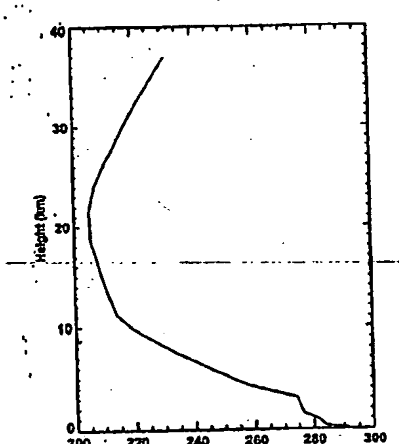

Figure 6(a)

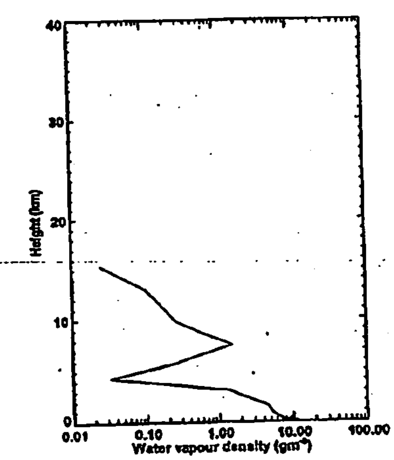

Figure 6(b)

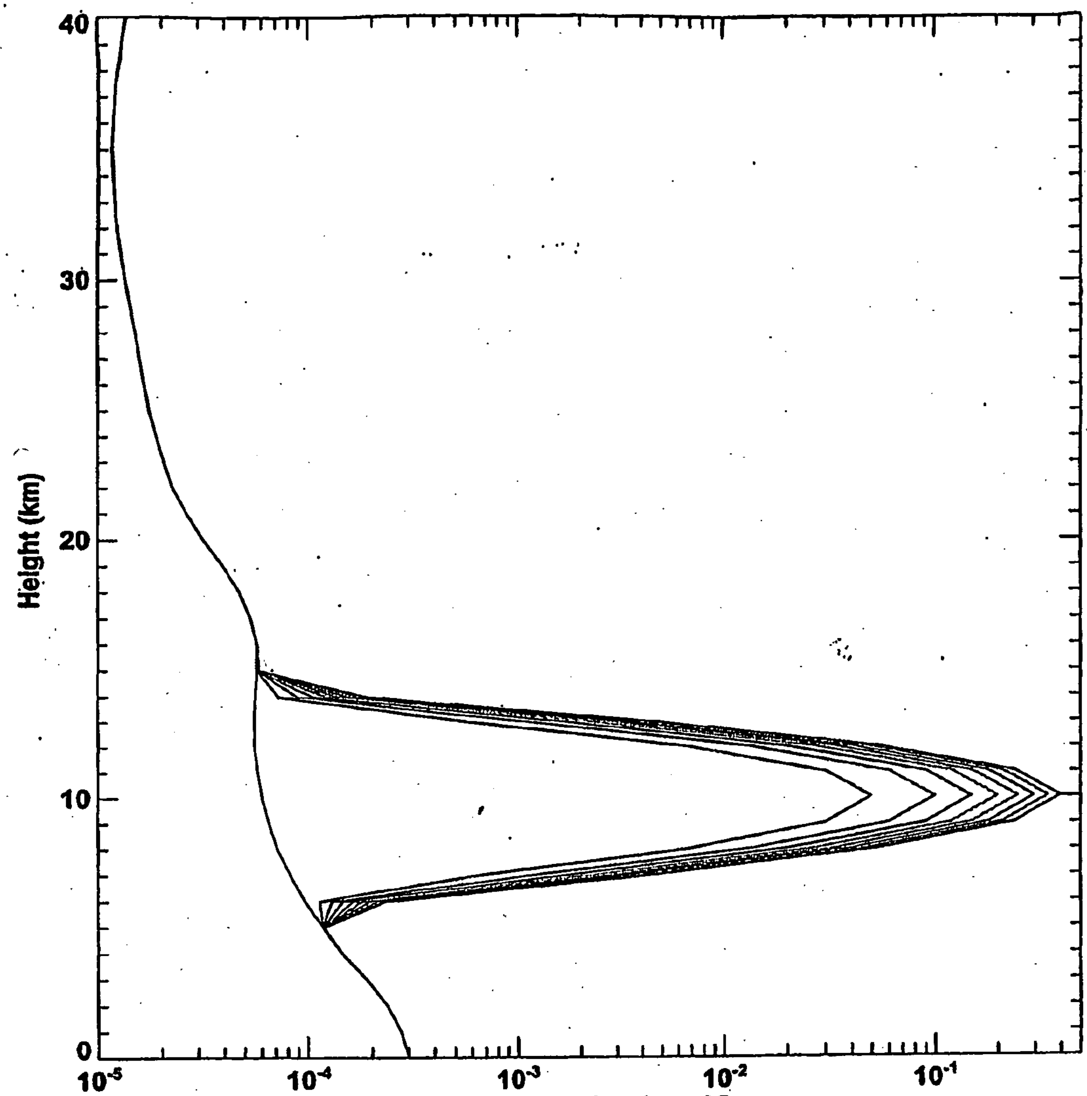

FIGURE 7

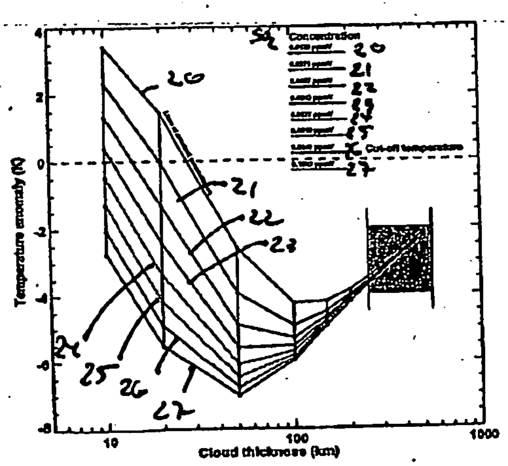

FIGURE 8

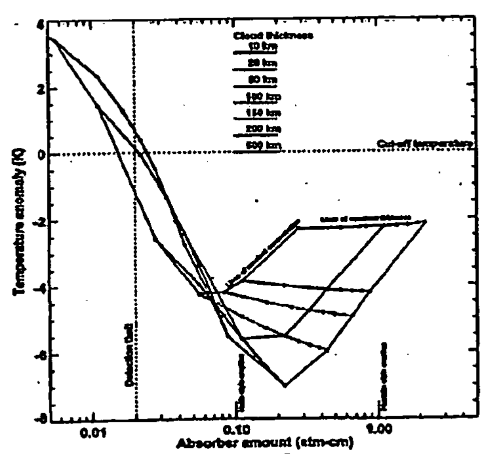

FIGURE 9